Comparison of Levelized Cost of Energy of superconducting direct drive generators for a 10 MW offshore wind turbine

A. B. Abrahamsen, D. Liu, N. Magnusson, A. Thomas, Z. Azar, E. Stehouwer, B. Hendriks, Gerrit-Jan Van Zinderen, F. Deng, Z. Chen, D. Karwatzki, A. Mertens, M. Parker, S. Finney and H. Polinder

***Abstract*—A method for comparing the Levelized Cost of Energy (LCoE) of different superconducting drive trains is introduced. The properties of a 10 MW MgB_2 superconducting direct drive generator are presented in terms weight scaled to a turbine with a rotor diameter up of 280 m and the cost break down of the nacelle components. The partial load efficiency of the generator is evaluated for a constant cooling power of 0, 50 kW and 100 kW and the annual energy production is used to determine the impact on Levelized Cost of Energy.**

***Index Terms*— Generators, Levelized Cost of Energy (LCoE), Superconductor, Wind Energy.**

I. Introduction

Superconducting generators have been proposed as an enabling technology for large offshore wind turbines, because the torque density of the superconducting generator can offer more compact and lightweight machines[1]. This hypothesis has been investigated as a part of the INNWIND.EU project, where 10-20 MW offshore turbines, targeting 50 m water depths in the North Sea, are designed [2]. These designs involve the development of turbine rotors with diameters of up to 280 m, drive trains, and both fixed and floating offshore foundations, all with a 25 year lifetime. To compare different concepts, the Levelized Cost of Energy (LCoE) is determined from the capital and operational expenditure (CAPEX and OPEX) of the equipment divided by the annual energy production summed over the lifetime.

This paper presents the final design of the INNWIND.EU 10 MW MgB_2 based superconducting direct drive generator, and the LCoE of the superconducting generator [3] is compared with the LCoE of a corresponding magnetic Pseudo Direct Drive (PDD) generator [4].

II. Levelized Cost Of Energy (LCoE)

A. Definition of LCoE with focus on generator

A method for comparing different energy producing technologies at the end of plant-life is to calculate the cost of the energy produced CoE by adding up all the costs C and divide with the total energy produced E, whereby $CoE = C/E$ [€/MWh].

One would however often like to compare technologies before they are constructed in order to determine which of them that will be the best investment [5]. This can be done by asking how much money should be reserved for a cost at the decision time ($t = 0$) $c_{0,i}$ in order to pay for the cost after i years c_i. The initial amount is smaller, because alternative investments with an interest rate of w has to be considered until the year of payment, whereby $c_i = c_{0,i}(1+w)^i$. The energy E_i produced during the years will result in an income i_i being proportional to the energy sales price s_i, but the income from producing the energy E_i in year i is worth less at the beginning of the investment $i_{0,i}$, because it takes time before it can be reinvested. Thus $i_{0,i} = E_i s_i \, 1/(1+w)^i$. The ratio between all the costs and the income recalculated to the beginning of the investment then becomes

Manuscript receipt and acceptance dates will be inserted here. The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7-ENERGY-2012-1-2STAGE under grant agreement No. 308974 (INNWIND.EU). *(Corresponding author: Asger Bech Abrahamsen, asab@dtu.dk)*

A. B. Abrahamsen is with the Department of Wind Energy , Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark (e-mail: asab@dtu.dk).

D. Liu and H. Polinder are with the Department of Electrical Sustainable Energy, Delft University of Technology, NL-2628 CD Delft, Netherlands (D.Liu@xemc-darwind.com and H.Polinder@tudelft.nl).

N. Magnusson is with the SINTEF Energy Research, Trondheim, Norway (Niklas.Magnusson@sintef.no).

A. Thomas and Z. Azar are with Siemens Wind Power limited, Sheffield S3 7HQ, United Kingdom (arwyn.thomas@siemens.com and ziad.azar@siemens.com).

E. Stehouwer and G.-J. Van Zinderen are with the Turbine Engineering DNV GL – Energy, Energieweg 17, 9743 AN Groningen, The Netherlands (ewoud.stehouwer@dnvgl.com and gerrit-jan.zinderen@dnvgl.com).

B. Hendriks is with the Knowledge Centre WMC, 1770 AA Wieringerwerf, The Netherlands (h.b.hendriks@wmc.eu).

F. Deng and Z. Chen are with the Department of Energy Technology, Aalborg University, Pontoppidanstraede 111, 9220 Aalborg East, Denmark (fde@et.aau.dk and zch@et.aau.dk).

D. Karwatzki and A. Mertens are with the Institute for Drive Systems and Power Electronics, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany (dennis.karwatzki@ial.uni-hannover.de and mertens@ial.uni-hannover.de).

M. Parker is with the Institute for Energy and Environment, University of Strathclyde, 204 George Street, Glasgow G1 1XW, United Kingdom (max.parker@strath.ac.uk).

S. Finney is with the School of engineering, The university of Edinburgh, Mayfield Road, Edinburgh, United Kingdom (Stephen.Finney@ed.ac.uk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier will be inserted here upon acceptance.

This is the accepted version of an article published in IEEE Transactions on Applied Superconductivity
DOI: 10.1109/TASC.2018.2810294

$$\frac{C}{I}=\frac{\sum_{i=0}^{LT} c_i\frac{1}{(1+w)^i}}{\sum_{i=0}^{LT} E_i s_i\frac{1}{(1+w)^i}}=\frac{1}{s_{i,c}}\frac{\sum_{i=0}^{LT} c_i\frac{1}{(1+w)^i}}{\sum_{i=0}^{LT} E_i\frac{1}{(1+w)^i}}=\frac{1}{s_{i,c}}LCoE \quad (1)$$

where LT is the life time, c_i is the cost in year i, w is the interest rate, E_i is the energy production in year i, s_i is the energy sales price in year i, $s_{i,c}$ is the energy price (assumed constant for all the years), and finally the Levelized Cost of Energy is denoted $LCoE$. If different energy technologies are in the same market then $s_{i,c}$ can be assumed to be the same, whereby the technology with the lowest $LCoE$ is the most favorable.

The above method can be used to compare the $LCoE$ of superconducting wind turbine generators with other drive train technologies by making some simplifying assumptions. First the cost terms are split into the CAPital EXpediture (CAPEX) and the OPerational EXpenditure (OPEX), which will be denoted C_i and O_i for the cost of the equipment and running cost in year i. The cost of the equipment is specified as the cost of the drive train C_D and the cost of the rest C_R of the turbine and foundation in case of an offshore turbine. These costs are payed at the beginning, whereas the operation cost o_i are assumed constant for every year and split into a drive train $o_{D,c}$ and rest of the turbine part $o_{R,c}$. The LCoE can then be written as

$$\mathrm{LCoE}=\frac{C_D+C_R}{\sum_{i=0}^{LT} E_i\frac{1}{(1+w)^i}}+\frac{\sum_{i=0}^{LT} o_i\frac{1}{(1+w)^i}}{\sum_{i=0}^{LT} E_i\frac{1}{(1+w)^i}}=\frac{C_D+C_R}{a\cdot E_{i,c}\cdot \mathrm{LT}}+\frac{o_{D,c}+o_{R,c}}{E_{i,c}} \quad (2)$$

where the Annual Energy Production (AEP) $E_{i,c}$ is assumed constant every year and the levelizing factor a is introduced as

$$a=\frac{1}{LT}\sum_{i=0}^{LT}\frac{1}{(1+w)^i} \quad (3)$$

The two terms in equation (2) can be considered the CAPEX and the OPEX contributions to LCoE.

An interest rate w = 5.75 % and a life time LT = 25 years can be considered as constants resulting in a = 0.55. The Annual Energy Production will depend on the wind resource characterized by a Weibull distribution and the losses of the drive trains. The cost of the drive train C_D can be found from the materials used in the design, but the operation expenditures are hard to determine before full scale demonstration of the superconducting generators have been evaluated. Thus the operation expenditures are assumed to be the level observed of other previous offshore wind turbines $O/E_{i,C}$ = 24 €/MWh [11].

B. *Sensitivity of LCoE to generator and turbine properties*

One can determine the sensitivity of LCoE due to the parameters of eq. (2) by introducing variations

$$\frac{\Delta LCoE}{LCoE_0}=-\frac{\Delta E_{i,c}}{E_{i,c0}} +\frac{LCoE_{CAPEX}}{LCoE_0}\left(\frac{\Delta C_D}{C_{D,0}+\ C_{R,0}}+\frac{\Delta C_R}{C_{D,0}+\ C_{R,0}}-\frac{\Delta a}{a_0}-\frac{\Delta LT}{LT_0}\right) +\frac{LCoE_{OPEX}}{LCoE_0}\left(\frac{\Delta O_{D,C}}{O_{D,C0}+O_{R,C0}}+\frac{\Delta O_{R,C}}{O_{D,C0}+O_{R,C0}}\right) \quad (4)$$

where the $\Delta E_{i,c}/E_{i,c0}$ is the relative change of the annual energy production and similar for the other parameters. The ratios $\mathrm{LCoE_{Capex}}/\mathrm{LCoE_0}$ and $\mathrm{LCoE_{Opex}}/\mathrm{LCoE_0}$ are estimated to be 0.72 and 0.28 respectively by using a cost of the turbine and foundations being C_R ~ 27 M€ [6,7,11].

III. 10 MW MgB_2 GENERATOR

A. *Generator topology*

A series of different MgB_2 based superconducting generator topologies have been investigated by defining the different active materials of the pole and then varying the dimensions in order to obtain the torque of the 10 MW INNWIND.EU reference turbine and to optimize for the lowest LCoE[6,7]. The costs of the generators are calculated based on the assumed unit cost of the active materials, being 3 mm x 0.7 mm MgB_2 tape with a copper strip from Columbus at a cost of 4 €/m [8], copper armature windings (15 €/kg), magnetic steel laminates (3 €/kg), and glass fiber (15 €/m). These unit costs represent the cost that the active material have in the final generator and include the profit of the manufacturing companies[9]. The conclusion from the investigations of [6,7] is that it is much easier to obtain the torque and low cost from the fully iron-cored MgB_2 generator with the current properties of the MgB_2 tapes, but at the expense of a higher active mass. In the INNWIND.EU project it was investigated if a cost reduction of the tower and foundations could be gained from a possible weight reduction of the superconducting generator, but it was found that reducing the tower top mass would shift a critical resonance of the tower and foundation closer to the blade passing excitation frequency, and thereby reduce the life time of the foundation[10]. Thus, the design philosophy for the INNWIND.EU MgB_2 generator was changed from “light weight and not too expensive” to “cheap and not too heavy”. In terms of (2) this means that the cost of the rest of the structure C_R is not expected to change much with changes in the drive train mass.

B. *Front mounted generator in nacelle*

The optimized active materials of the MgB_2 generators using the method of [6,7] where used to determine an appropriate aspect ratio of the 10 MW generator to be able to integrate the generator into a nacelle, where the generator is mounted in front of the turbine blades as shown in Fig. 1. This configuration has been denoted the king pin concept, because a static pin is going through the hub that is holding the 3 blades and is supported on both sides by roller bearings. It has been found that a D = 8.4 m and L = 1.3 m MgB_2 generator seems to match the dimensions of the King-pin nacelle and the resulting weight of the generator is 286 tons.

Table I shows the main properties of the 10 MW MgB_2 generator [11] and Fig. 2 shows the expected mass scaling of the generator, blade and nacelle as function of the turbine rotor diameter approaching $D_{turbine}$ = 280 m by using the scaling principles of [12]. The unit cost of the structural steel used for the nacelle is 3-4 €/kg.

C. *Cryostats and cooling system*

The choice of the iron-cored topology of the INNWIND.EU 10 MW MgB_2 generator calls for a cryostat concept, where warm magnetic steel laminated poles go through the MgB_2 racetrack coils. This concept has been investigated in the Su-

This is the accepted version of an article published in IEEE Transactions on Applied Superconductivity
DOI: 10.1109/TASC.2018.2810294

prapower project [13] and has been projected onto the INNWIND.EU generator by assuming that a similar heat load will be present. This has been used to estimate the cryocooler coldheads and compressors demand, whereby the cost of the cryogenics system has been determined [11]. It is found that about 15 coldheads will be needed to provide the cooling and a loss of 104 kW, corresponding to 1 % of the full rated power of the turbine, is needed to run the compressors. Fig. 3 shows the cost and mass break down of the nacelle components of the 10 MW MgB_2 generator layout, including the cryostat and compressor cost [11].

D. Efficiency of superconducting generator

The efficiency of the 10 MW MgB_2 superconducting generator has been determined from the joule losses in the armature windings, the hysteresis losses of the magnetic steel laminates, and the eddy current losses, all as function of the wind speed of the 10 MW INNWIND.EU reference turbine [6,7]. Appropriate power converters for the 10 MW generator have also been investigated [14] and the efficiency of the power converter is included in Fig. 4. The design Weibull wind distribution corresponding to an IEC class Ia wind resource having a mean wind speed of v_{ave} = 10.0 m/s and a shape parameter of k = 2 [15] is also shown. Thus one can then calculate the annual energy production of the 10 MW turbine using the mechanical power curve of the rotor blades $P_{mech}(v)$ [15] adjusted for the partial load efficiency $\varepsilon(v)$ and integrate that over the wind speed distribution

$$E_{i,C} = \int_{v_{cut-in}}^{v_{cut-out}} P_{mech}(v)\varepsilon(v)P_{Weibull}(v)dv \qquad (5)$$

where $v_{cut\text{-}in}$ = 4 m/s and v_{cutout} = 25 m/s is giving the operational wind speed range. Once the wind speed reaches rated wind speed at v_{rated} = 11.4 m/s, the turbine blades are pitched and the turbine produces the rated power. Thus, above rated wind speed, the output is P = 10 MW.

IV. Comparison of LCoE

Fig 4. shows the partial load efficiency of the 10 MW MgB_2 generator when including a constant cooling power of 0, 50 or 100 kW, as well as the 10 MW RBCO based direct drive and a magnetic Pseudo Direct Drive (PDD) of INNWIND.EU. The annual energy production of the different drive trains has been evaluated using (5) and the impact on LCoE from (4) is shown in table II. The pure annual energy production with no losses have been used as the baseline and the increase of LCoE is therefore with respect to a loss free drive train. By summing the drive train costs in Fig. 3 to C_D ~ 2.6 M€ including power converter, one can estimate the LCoE of the 10 MW MgB_2 generator using (2) to be

$$\mathrm{LCoE} = \frac{2.6\ \mathrm{M€} + 27\ \mathrm{M€}}{0.55 \cdot 48.3\,\frac{\mathrm{GWh}}{\mathrm{y}} \cdot 25\mathrm{y}} + 24\,\frac{€}{\mathrm{MWh}} = 68.6\ €/MWh \qquad (6)$$

This estimate is however considerably higher than most recent LCoE levels for offshore wind around 40 €/MWh [17] and indicates that the material unit cost should be lowered in order to match absolute cost values.

The impact of the cost of the different drive trains can in principle be done, but a challenge is how to ensure the same inclusion of manufacturing cost and profit. One can however determine the change of LCoE if the drive train cost CD is reduced to half. From the second term of (4) one obtains

$$\frac{LCoE_{CAPEX}}{LCoE_0}\left(\frac{\Delta C_D}{C_{D,0} + C_{R,0}}\right) = 0.72 \cdot \frac{-1.3\ M€}{2.6\ \mathrm{M€} + 27\mathrm{M€}} = -3.2\ \% \qquad (7)$$

V. Discussion

The analysis of the 10 MW MgB_2 generator shows that the constant power consumption of 100 kW of the cooling machines reduces the partial load efficiency of the turbine and effort to reduce the cooling power to about 50 kW will be needed and could reduce LCoE by about 0.6 %. It should however be noted that the Pseudo Direct Drive generator based on permanent magnets is more efficient than the superconducting drive train even when the cooling is neglected. Secondly it is seen that reducing the cost of the superconducting drive train to half can result in a reduction of the LCoE of about 3 %, which will also be needed to compete with the PDD.

VI. Conclusion

A method for comparing the levelized cost of energy of different superconducting drive trains have been used to indicate that the constant cooling loss of 100 kW of the 10 MW MgB_2 generator should be reduced to 50 kW in order to obtain a better partial load efficiency. Secondly a reduction of the drive train cost from 2.6 M€ to half would be beneficial. A reduction of LCoE of 0.6 % and about 3 % would result.

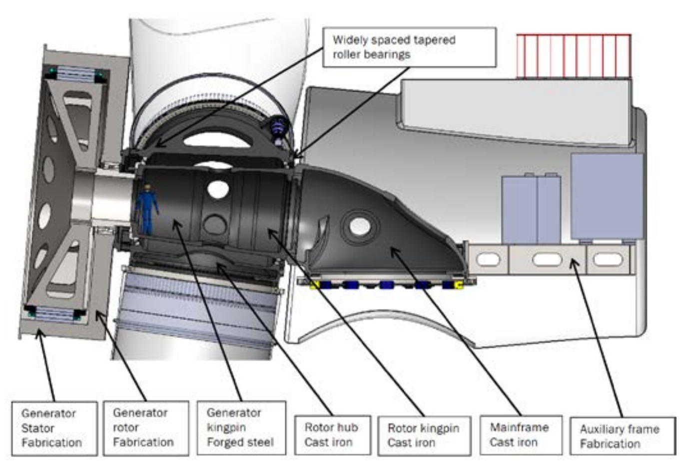

Fig. 1. Cross section view of the INNWIND.EU nacelle with the 10 MW MgB_2 generator mounted in front of the turbine blades[12]. The inner and stationary structure of the generator is attached to the stationary King-pin going through the rotor hub and connected to the main frame.

This is the accepted version of an article published in IEEE Transactions on Applied Superconductivity
DOI: 10.1109/TASC.2018.2810294

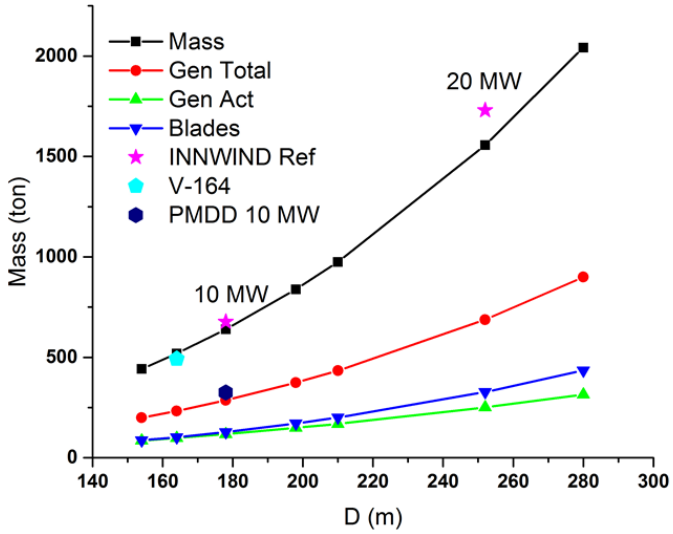

Fig. 2. Mass scaling of the main components of the front mounted MgB_2 superconducting direct drive generator as function of the turbine rotor diameter. The MgB_2 generator active materials mass (green) are added to the structural generator mass whereby the total generator mass (red) is obtained. By adding also the blade mass (blue) and the nacelle mass then the Rotor Nacelle Assembly (RNA) mass (black) is obtained. The RNA of the INNWIND.EU reference designs for P = 10 MW and 20 MW are shown (stars) as well as the RNA of the Vestas V-164 [16] and the total generator mass of a 10 MW permanent direct drive generator design by Polinder [9].

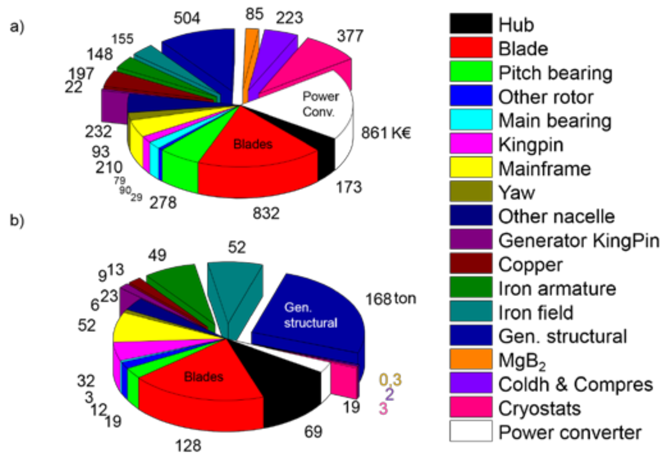

Fig. 3. 10 MW MgB_2 superconducting direct drive wind turbine rotor, generator and nacelles component cost and weight breakdown. a) Component cost in [k€] and b) component weight in [ton] according to the components outlined in [12]. The components associated with the superconducting drive train have been displaced from the center.

TABLE II

ANNUAL ENERGY PRODUCTION OF DRIVE TRAINS

Drive train	E_i [GWh/year]	$\Delta LCoE/LCoE_0$ [%]
MgB_2 – No cooling loss included	48.8	1.9
MgB_2 – 50 kW cooling loss included	48.6	2.5
MgB_2 – 100 kW cooling loss included	48.3	3.1
RBCO – No cooling loss included	48.5	2.6
Pseudo Direct drive (PDD)	49.1	1.3
10 MW reference turbine with no loss	49.8	0.0

TABLE I

PROPERTIES OF MgB_2 DIRECT DRIVE GENERATORS

Power [MW]	10	20
Turbine rotor diameter [m]	178	252
Rated Speed [RPM]	9.65	7.13
Rated line-to-line voltage [V]	3300	6600
Specific electrical loading [kA/m]	75	75
Field current density in coil (20 K) [A/mm^2]	111	115
Field current density in tape (20 K) [A/mm^2]	178	184
Stator outer diameter D_s [m]	8.4	10.8
Number of phases m	3	3
Slots per pole per phase q	5	5
Pole pitch τ_p [mm]	471	471
Number of pole pairs p	28	36
Frequency f_e [Hz]	4.5	4.2
Axial stack length L_s [m]	1.31	2.25
Shear stress σ_t [kPa]	72.3	71.6
Normal stress σ_r [kPa]	486	469
$D_s^2 L_s$ [m^3]	92.4	262.4
Air gap length g [mm]	8.4	10.8
MgB_2 field winding (incl. end) [ton]	0.32	0.52
Rotor iron mass [ton]	51.8	111.5
Cryostat mass [ton]	3.4	8.9
Stator iron mass [ton]	49.4	106.8
Copper mass (incl- end) [ton]	13.1	24.3
Total rotor mass [ton]	55.5	120.4
Total stator mass [ton]	62.4	131.0
Total active mass [ton]	118	251
Structural mass [ton]	168	437
Total generator mass [ton]	286	688

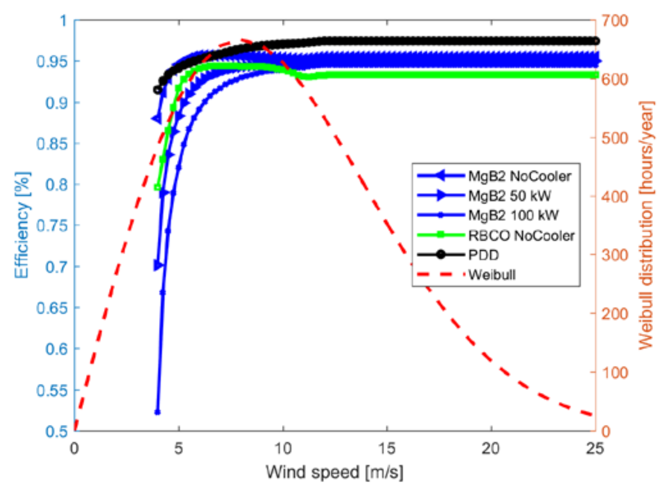

Fig. 4. Efficiency of the 10 MW MgB_2 generator with a constant power consumption of the cryogenic cooling system of 0, 50 kW and 100 kW, a 10 MW coated conductor RBCO based generator [3] without cryogenic cooling consumption and the magnetic Pseudo Direct Drive (PDD) generator [4] investigated in the INNWIND.EU project. The Weibull wind distribution is shown on the right hand axis.

This is the accepted version of an article published in IEEE Transactions on Applied Superconductivity
DOI: 10.1109/TASC.2018.2810294

REFERENCES

[1] Gregory Snitchler, Bruce Gamble, Christopher King and Peter Winn, "10 MW Class Superconductor Wind Turbine Generators", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 21, NO. 3, 1089 (2011).

[2] INNWIND.EU project we site, www.innwind.eu. Accessed on: Sep. 20, 2017.

[3] INWIND.EU deliverable report D3.12, "Investigation of Super-Conducting Direct Drive Generators"

[4] INNWIND.EU deliverable report D3.21, "Design and PI of PDD generator"

[5] W. Short, D. J. Packey and T. Holt, "A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies", NREL report NREL/TP-462-5173 (1995).

[6] Dong Liu, Henk Polinder, Asger Bech Abrahamsen and Jan A. Ferreira, Fellow, "Topology Comparison of Superconducting Generators for 10-MW Direct-Drive Wind Turbines: Cost of Energy Based", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, 5202007 (2017).

[7] Dong Liu, "INCREASING THE FEASIBILITY OF SUPERCONDUCTING GENERATORS FOR 10 MW DIRECT-DRIVE WIND TURBINES", PhD Thesis, Technical University of Delft 2017. Available at http://repository.tudelft.nl/.

[8] Columbus Superconductors web site: http://www.columbussuperconductors.com/ . Accessed on: Sep. 20, 2017.

[9] H. Polinder, D. Bang R.P.J.O.M. van Rooij A.S. McDonald, M.A. Mueller, "10 MW Wind Turbine Direct-Drive Generator Design with Pitch or Active Speed Stall Control", Electric Machines & Drives Conference, 2007. IEMDC '07. IEEE International, p. 1319 (2007).

[10] INWIND.EU deliverable report D4.34, "Innovative Design of a 10 MW Steel-Type Jacket"

[11] INNWIND.EU deliverable report D3.11, "Direct drive superconducting generators for INNWIND.EU wind turbines" (under external review)

[12] INNWIND.EU deliverable report D3.41, "Conceptual nacelle designs of 10-20 MW wind turbines "

[13] Suprapower website: www.suprapower.eu

[14] INNWIND.EU deliverable report D3.31, "Converter designs tailored to SC and PDD concepts"

[15] INNWIND.EU deliverable report D1.21, "Reference Wind Turbine Report"

[16] E. de Vries, "Close up - Vestas V164-8.0 nacelle and hub". *Wind Power Mountly* September 9 (2013)

[17] New Energy Update, "Europe's new record offshore LCOE forecast at 40 euros/MWh", 5 December (2016)

This is the accepted version of an article published in IEEE Transactions on Applied Superconductivity
DOI: 10.1109/TASC.2018.2810294